17TH ADVANCED BEAM DYNAMICS WORKSHOP ON

FUTURE LIGHT SOURCES

Storage Ring-Based Light Sources

V. Litvinenko, Duke University

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Storage Ring-based Light Sources

Vladimir Litvinenko

Duke University, Department of Physics, FEL Laboratory, Durham, NC, USA

More than fifty ring-based fully or partly dedicated light sources are in operation around the globe at present time and large number is in the construction or development phase. These rings operate at energies from few hundreds MeV to 14 GeV covering photons spectra from IR to soft γ-rays.

This talk will be focused on three topics relevant to storage ring-based light sources. We will start from brief overview of existing ring-based sources and drawing a generic picture of "typical" second and third generation storage ring-based light sources to establish the base line. The table with range of established machine and light source parameters will be presented. It will be followed by discussion of new trends in the development of ring-based light sources which push the envelope of presently established parameters by reduction of e-beam emittances, increase of beam currents, shortening pulses, increasing coherence, etc. Third part of talk will be dedicated to evaluation of future capabilities and limitations of ring-based light sources. Few examples of new capabilities will be presented.

Content:

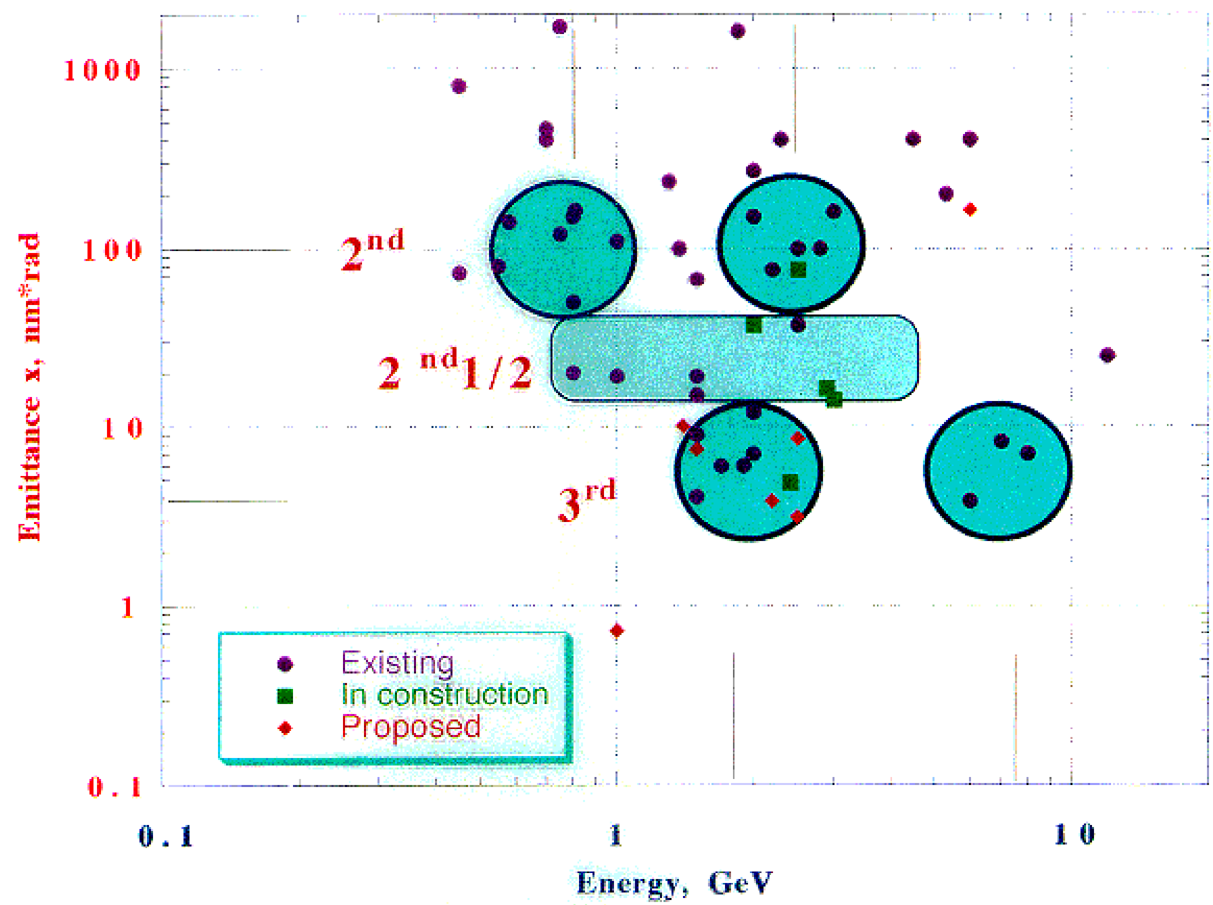
- Brief overview of existing ring-based sources
- Portrait of 2nd generation light source
  - VUV
  - X-Ray
- Portrait of 3rd generation light source
  - VUV
  - X-Ray
- New(?) trends in the development of light sources
- future capabilities
- and limitations of ring-based light sources

Table 1. Main parameters of existing and proposed SR facilities. Type: P(artially) Ded(icated), Par(asitic); Status: Op(erational), Comm(issioning), Constr(uction), Prop(osed); C = circumference; E_{inj}, E_{op} = injection, operational energy (most typical energy underlined); I_b = actual/nominal max. beam current (mA), ε_x, ε_y = horiz., vert. emittances (nm rad) (at typical energy); Op.h. = total no. hours scheduled operation in '98; User% = percentage of Op.h. for SR users in '98; Eff. = op. efficiency (%) for users in '97; ID/NID = no. installed/total no. ID straights. († FY97)

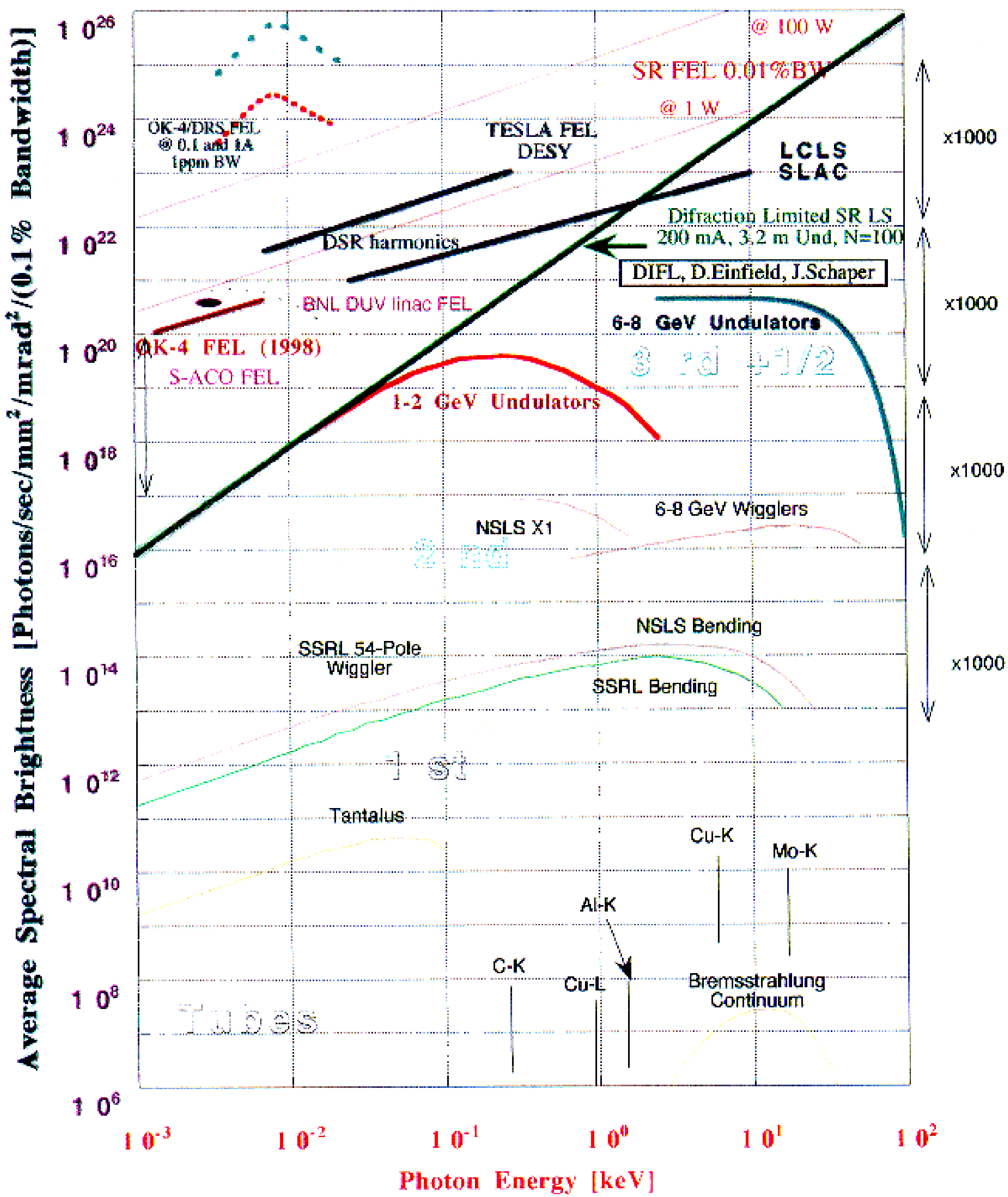
Facility	Type	Status	C (m)	E_{inj}	E_{op}	I_b	ε_x, ε_y	Op.h.	User%	Eff.	ID/NID
Brazil											
LNLS UVX	Ded.	Op. '97	93	0.12	1.37	100	100, 0.4	3625	63	96	0/4
Canada											
CLS	Ded.	Prop.	147	2.9	2.9	500	16.3, -	-	-	-	-/10
China											
BEPC	PDed.	Op. '91	240	1.3	2.2	70	76, 0.76	600	88	-	2/-
HNSRL	Ded.	Op. '91	66	0.2	0.8	150	150, 13	4600	50	89	2/3
SSRF	Ded.	Prop.	345	2.2	2.2	400	3.8, -	-	-	-	-/16
Denmark											
ASTRID	PDed.	Op. '94	40	0.1	0.58	175	140, 14	6800	47	95	1/1
ASTRID II	Ded.	Prop.	76	0.5	0.6-1.4	200	10, 1	-	-	-	-/5
England											
DIAMOND	Ded.	Prop.	346	3.0	3.0	300	14, 0.14	-	-	-	-/16
SRS	Ded.	Op. '81	96	0.6	2.0	250	150, 5	6440	88	90	3/5
France											
DCI	Ded.	Op. '75	95	1.85	1.85	325	1600, 190	3823	98	90	1/2
ESRF	Ded.	Op. '92	844	6	6	200	3.8, 0.03	6800	83	96	27/28
SOLEIL	Ded.	Prop.	337	2.5	2.5	500	3.1, 0.03	-	-	-	-/14
SuperACO	Ded.	Op. '85	72	0.8	0.8	420	20, 20	3440	91	89	6/6
Germany											
ANKA	Ded.	Constr.	110	0.5	2.5	400	76, 1.5	-	-	-	0/5
BESSY I	Ded.	Op. '81	62	0.8	0.3-0.8	750	50, 2.5	2000	90		3/3
BESSY II	Ded.	Comm.	240	1.9	1.7 (1.9)	100	6, < 0.02	-	-	-	1/14
DELTA	PDed.	Comm.	115	1.5	0.4-1.5	200	15, 0.06	2700	-	-	1/4
DORIS III	Ded.	Op. '73	289	4.5	4.5	120	400, 12	6384	84	91	10/11
ELSA	PDed.	Op. '88	164	1.6	1.6,2.3	80	400, 8	4000	38	-	0/1
PETRA	PDed.+Par.	Op.	2304	7	12	40	25, 0.75	4400	23	-	1/1
India											
INDUS I	Ded.	Comm.	19	0.45	0.45	100	73, 0.73	-	-	-	0/1
INDUS II	Ded.	Constr.	172	0.7	2.0-2.5	300	37, 3.7	-	-	-	0/5
Italy											
ELETTRA	Ded.	Op. '94	259	1.0	2.0	300	7, 0.1	6528	81	93	6/11
Japan											
HiSOR	Ded.	Op. '97	22	0.15	0.7	-	400, -	-	-	-	2/2
New Subaru	Ded.	Constr.	119	1.0	0.5-1.5	100	67, 6.7	-	-	-	0/4
PF	Ded.	Op. '82	187	2.5	2.5, 3.0	400	37, 0.37	4250	80	94	6/7
PF-AR	Ded.	Prop.	377	2.5	6	100	163, 1.63	-	-	-	-/8
SPRING-8	Ded.	Op. '97	1436	8	8	100	7, 0.07	4000	75	97	8/38
TERAS	Ded.	Op. '81	31	0.31	0.75	250	1700, 1700	2000	80	100	2/2
Tohuku U.	Ded.	Prop.	194	1.2	1.5-1.8	300	7.4, -	-	-	-	-/12
UVSOR	Ded.	Op. '83	53	0.6	0.75	240	120, 3	3000	80	99	3/3
VSX	Ded.	Prop.	200	0.3	1.0	200	1, -	-	-	-	-/2
Korea											
PLS	Ded.	Op. '95	281	2.0	2.0	200	12, 0.08	5000	80	91	1/10
Russia											
KSRS SIB.1	Ded.	Op. '83	8.7	0.075	0.45	230	800, -	-	-	-	0/0
KSRS SIB.2	Ded.	Op. '96	124	0.45	2.5	72	100, 1	2500	-	-	0/9
VEPP-2M	PDed.	Op. '72	18	0.6	0.7	300	460, 4.6	-	-	-	2/3
VEPP-3	Par.	Op. '73	74	0.35	2.0	250	270, 2.7	-	-	-	1/2
VEPP-4M	Par.	Op. '98	366	1.8	6.0	100	400, 120	-	-	-	2/4
Spain											
LSB	Ded.	Prop.	252	2.5	2.5	250	8.5, 0.1	-	-	-	-/10
Sweden											
MAX I	PDed.	Op. '86	32	0.1	0.55	250	80, 8	6000	58	95	1/2
MAX II	Ded.	Op. '95	90	0.5	1.5	250	9, 0.9	5000	90	80	5/8
Switzerland											
SLS	Ded.	Constr.	288	2.4	2.4	400	4.8, 0.05	-	-	-	0/9
Taiwan											
TLS	Ded.	Op. '93	120	1.3	1.5	200	27, 0.66	5500	76	90	3/4
U.S.A.											
ALADDIN	Ded.	Op. '85	88	0.108	0.8-1.0	240	110, 3.7	5200	85	95	4/4
ALS	Ded.	Op. '93	197	1.5	1.5, 1.9	400	6, 0.03	6520	85	96	6/10
APS	Ded.	Op. '97	1104	7	7	100	8, 0.08	5900	78	-	18/35
CAMD	Ded.	Op. '92	55	0.18	1.3-1.5	200	235, 2.35	3000	83	-	0/2
CHESS	Par.	Op. '80	795	5.3	5.3	190	200, 20	5333	75	-	2/2
NSLS VUV	Ded.	Op. '83	51	0.75	0.8	850	160, 3	6853†	75†	96†	5/7
NSLS X-ray	Ded.	Op. '82	170	0.75	2.58, 2.8	350	90, 0.1	7014†	81†	98†	2/2
SPEAR II	Ded.	Op. '73	234	2.25	3.0	100	160, 1.6	6900	77	96	6/10
SURF II	Ded.	Op. '74	5.3	0.01	0.3	200	- -	-	-	-	0/0

EPAC'98 R. Walker

Storage Ring Ligth Sources in the World



Average Spectral Brightness



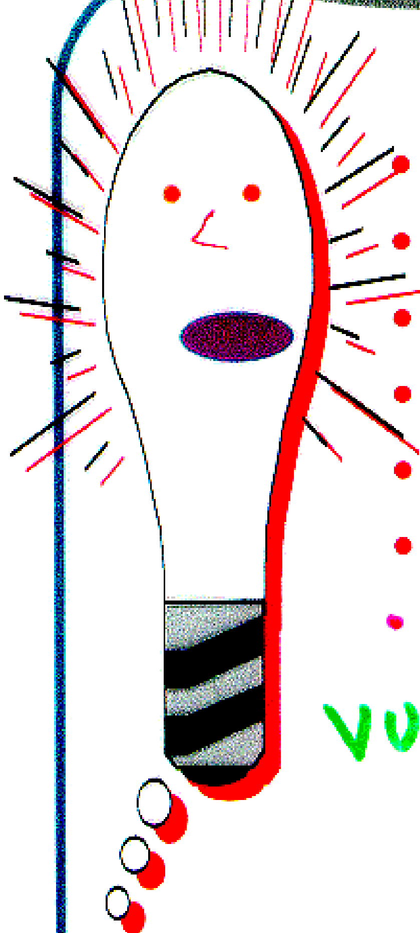
Portrait of 2nd Generation VUV source

# of rings		7
e-Beam energy, GeV		0.85 ± 0.2
Circumference, m		60 ± 15
Emittances, nm.rad		$\varepsilon_x=140\pm50$; $\varepsilon_y=6\pm5$
Photons energies		0.01 eV - 1 KeV
# beamlines		5 - 30
e-beam current, mA		150 -950
Lifetime, h		5 - 10
Brightness:	BM	10^{13} (< 1 KeV)
	ID	10^{16} (< 200 eV)
	ID	10^{14} (< 1 KeV)
Reliability		98±(?) %

Portrait of 2nd Generation X-ray source

# of rings	5 exist, 1 in construction
e-Beam energy, GeV	2.6 ± 0.4
Circumference, m	150 ± 80
Emittances, nm.rad	ε_x=100±40; ε_y =0.8±0.6
	-> 25-40 (18) (PF, SPEARIII, NSLS...)
Photons energies	up to 22 KeV
# beamlines	50+
e-beam current, mA	150 -300 → 400
Lifetime, h	10 - 20
Brightness: BM	10^{14} (~ 5 KeV)
U	10^{17} (~ 1 keV)
W	10^{15} (~ 5 KeV)
Reliability	98±(?) %

Trends with 2nd Generation sources

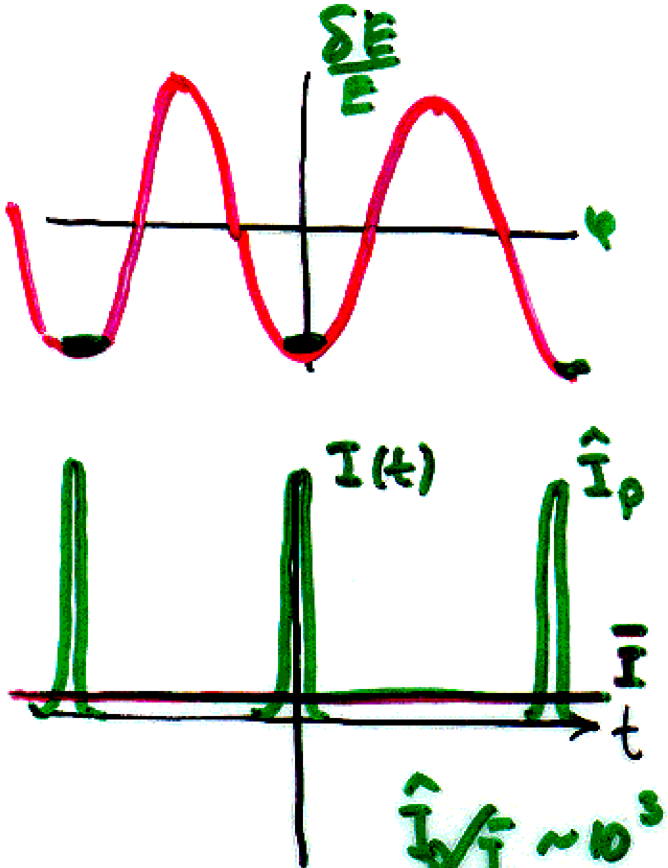


- High average current and high flux
- Lower emittances and higher brightness
- Longitudinal and Transverse MB feed-backs
- In-vacuum undulators
- IR ports
- Super-conducting wigglers
- IDs with variable polarization

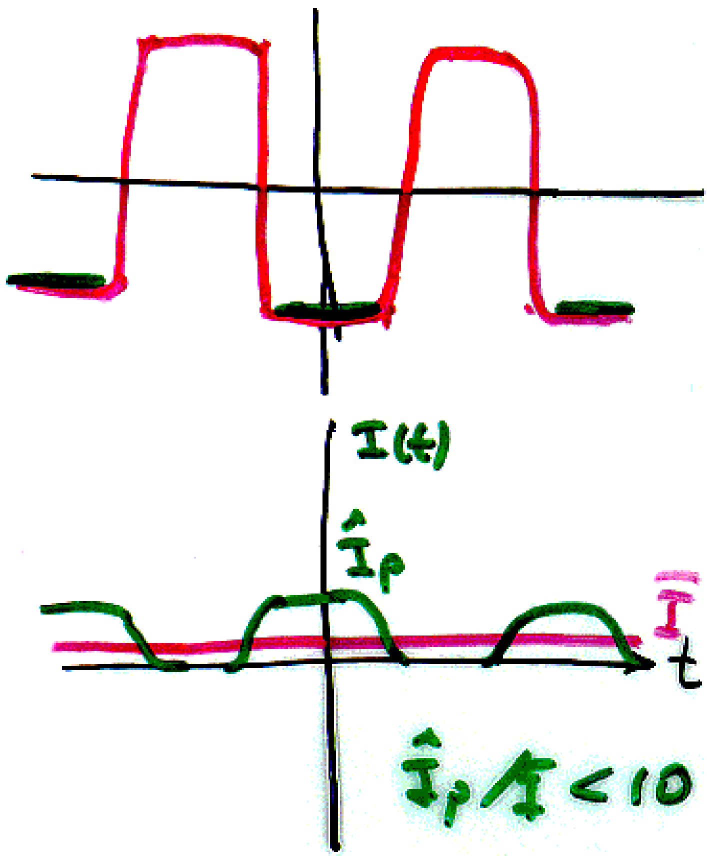
VUV – long bunches (harm. RF) to improve life time $\hat{I}_p/\bar{I} \lesssim 10$

X-ray – lower ε_x & higher brightness

Standard RF



"Flat RF"



⇒ Lower density → longer lifetime

⇒ Lower $\hat{I}_p$ → less instabilities

→ higher $\bar{I}$

⇒ Low peak brightness

⇒ Limited time-resolved applications

2^{nd} Generation LS

- doing extremelly well
- have very good reviews & strong user support
- still improving to compete with 3^{rd} generation (lower E_x, longer T_L)
- reliable almost as a light bulb !

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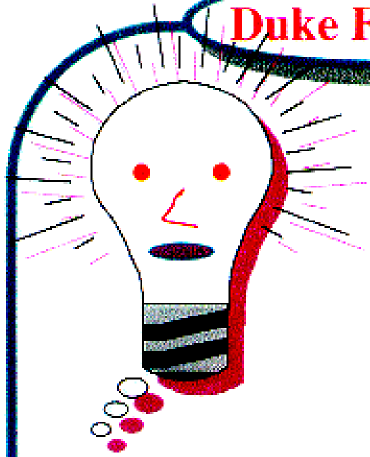

Portrait of 3rd Generation VUV source

# of rings		7 exist; 4 proposed 3 under constructions
e-Beam energy, GeV		1.5 - 3
Circumference, m		90 - 346
Emittances, nm.rad		ε_x=3-19; ε_y =0.02-0.9
Photons energies		up to 15 KeV
# beamlines		~ 50
e-beam current, mA		100 -500
Lifetime, h		up to 15
Brightness:	BM	10^{16} (~ 2 KeV)
	U	$5\cdot 10^{\cancel{20}\,19}$ (~ 1 keV)
Reliability		high and improving

<u>3rd Generation SR LS are the SUCCESS!</u>

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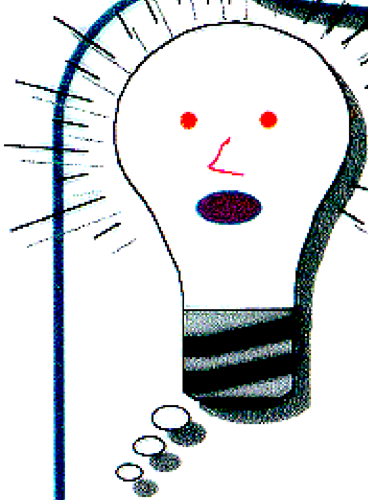

Portrait of 3rd Generation hard-X-ray source

# of rings		3
e-Beam energy, GeV		6 - 8
Circumference, m		844 1436
Emittances, nm.rad		ε_x=3-8; ε_y =0.03-0.08
Photons energies		up to 100 KeV
# beamlines		100 +
e-beam current, mA		100 -200
Lifetime, h		up to 70
Brightness:	BM	10^{16} (~ 10 KeV)
	U	6.10^{20} (~ 10 keV)
Reliability		high and improving

<u>3rd Generation SR LS are the SUCCESS!</u>

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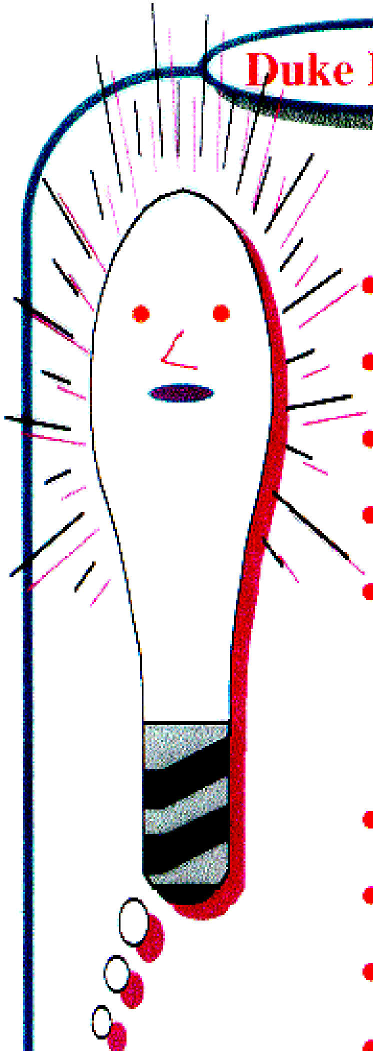

Trends with 3rd Generation VUV source

- More average and peak current
- Use of undulators with elliptical polarization
- Increase of energy to and above 2 GeV
- Energy ramping and plans for full energy inj.
- Compromise between brightness & lifetime (large coupling, limited LMBI, flat RF to elongate bunches->~50 h lt)
- Longitudinal and Transverse MB feed-backs
- In-vacuum undulators
- Super-bends
- Longer straight sections
- XUV Free Electron Lasers
- IR ports
- Tests of top-up injection

• smaller apertures (3mm)
• Al-cooled vac. chambers
• Top-up vs lower $\varepsilon_x \cdot \varepsilon_y$
• Larger dynamic E apor.

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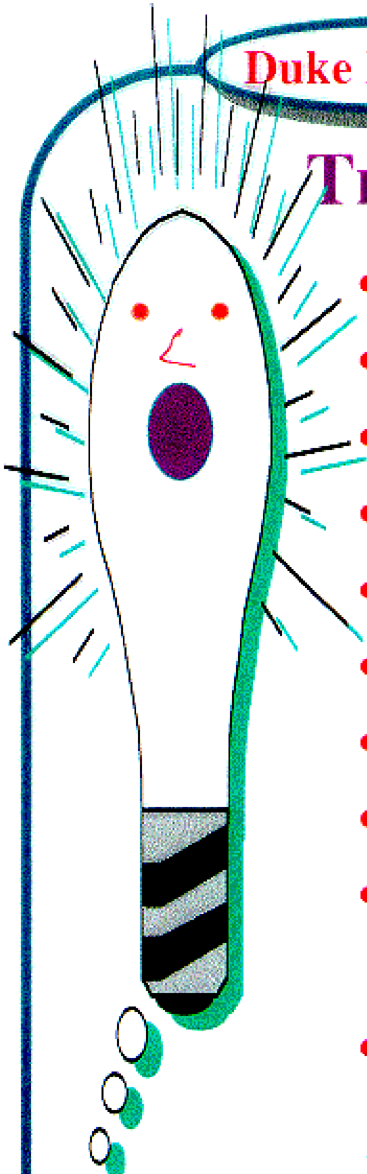
Life Time - limited by Touschek



Trends with 3rd Generation hard-X-Ray source

- More average and peak current
- Use of undulators with elliptical polarization
- Higher brightness
  - Better beam-position stability (1/3 μrad)
- Lower coupling
  - Horizontal focusing using beams with $\alpha_x \neq 0$
- Smaller horizontal emittance
- Longitudinal and Transverse MB feed-backs
- In-vacuum undulators
  - small apertures
- Better beam stability
- Intense short bunches with 200-300 A peak current
- Probing issues for 4-th GLS
  - Wigglers for 1 MeV SR
- Top-up
- e^- beams
- Larger dynamic E aperture & better Touschek lifetime
- Flexible SS

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3rd Generation LSs

- exceeded al designed parameter & become essentially 3½ generation light sources!
- very reliable & have growing user support
- still improving & providing additional BLs with higher fluxes and reasonable Bs.
- have potential to implement elements of next generation light sources (higher Bs, shorter pulses, FELs...)

Pushing the Envelope for Ring-based LS

- $\varepsilon_x \rightarrow$ 0.1 nm.rad (ESRF, 1 GeV, low current); <1 nm·rad (1 GeV, $\hat{I} \approx 300$ A, DR, VSX)
- $\varepsilon_y / \varepsilon_x < 0.1\%$ $\Rightarrow$ diffraction limited in y-plane $E_{ph} < 30$ keV
- Average Spectral Brightness $\frac{ph}{s \cdot \mu m^2 \cdot (10^{-3} BW)}$ $2 \cdot 10^{20}$ @ 10-20 keV; $4 \cdot 10^{19}$ ~300 eV; $3 \cdot 10^{20}$ 4-5 eV (FELs)
- Peak Sp. Brightness $5 \cdot 10^{23}$; $5 \cdot 10^{22}$; $3 \cdot 10^{26}$
- Shorter pulses ~10 psec - spontaneous, ~2.5 psec - FELs
  100 fs by laser energy modulation (LBL, Zholents)
- IDs with short λ_w $\rightarrow$ higher B @ higher E_{ph} (users!)
- Compton sources $\rightarrow$ move to γ-range or reduce E_{beam}
- 10 T @ 8 GeV $\rightarrow$ 1 MeV synchrotron radiation

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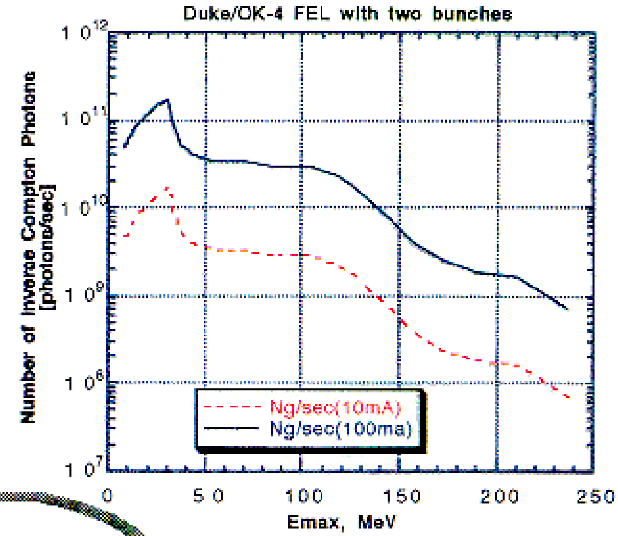
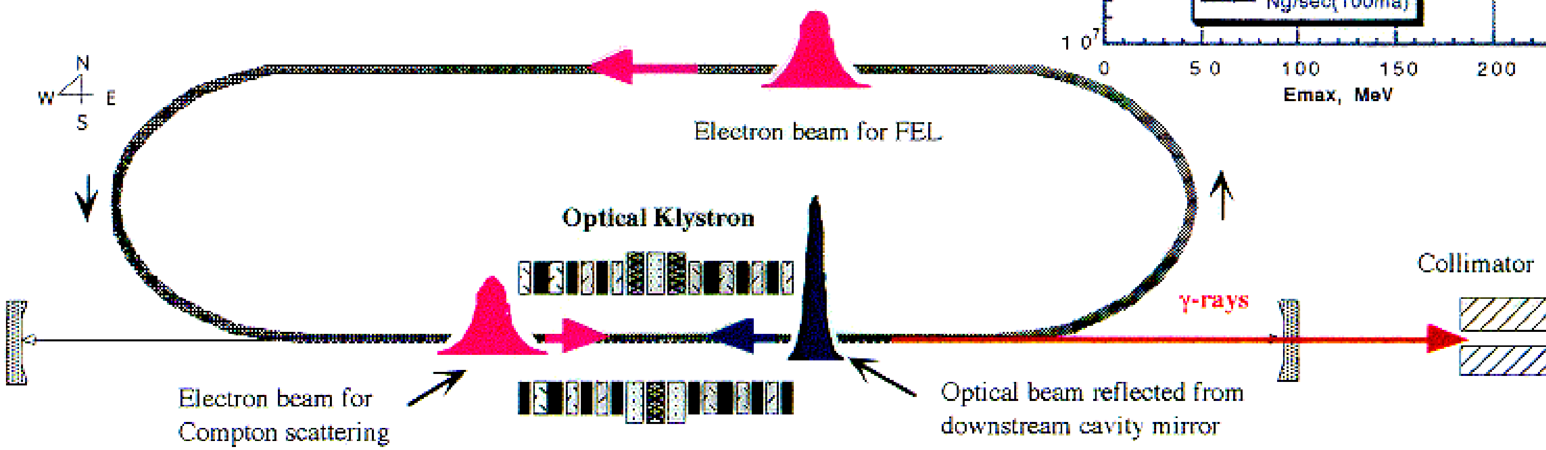
Compton γ-ray Production in the OK-4 FEL/Duke Storage Ring





Experimental Results

SR/FEL Parameters

$E_{electron}$ [MeV]	250-750
I [mA] per bunch	1-10
$P_{intracavity}$ [W]	1-25
λ_{FEL} [nm]	230-730
$\dot{N}_{photon}$ [sec^{-1}]	~ 10^{20}

γ-ray-beam Parameters

	Min	Max
$E_{\gamma, MAX}$ [MeV]	1.9	42
$\dot{N}_{\gamma,TOTAL}$ [sec^{-1}]	3 x 10^5	5 x 10^7
$\dot{N}_{\gamma,3\text{ mm collimator}}$ [sec^{-1}]	~ 10^3	~ 10^5
FWHM, %	0.5	1

Polarization (linear)	100%

Storage Ring FELs

- **MODEST Progress in last 10 years**
  - Slightly shorter wavelength 212 nm vs 240 nm
  - shorter pulses 2.5 ps vs 100 ps
  - higher gain per pass in UV >10% vs single %s
  - more average power ~200 mW vs ~20 mW
  - longer lasing time 10 hrs vs 1 hour
  - higher peak power 0.3 MW vs 0.01 MW
  - high average spectral brightness → $2\text{-}4 \cdot 10^{20}$ @ 5 eV
  - high peak —"— → $3 \cdot 10^{26}$ @ 5 eV

    (ph/sec/mm²/mrad²/10³ BW)
  - user programs ~ 1000 hrs
- **Progress was modest because of**
  - marginal efforts, small groups, lack of funding...
  - use of 1st, 2nd and 2½ generation storage rings with low (~10s A) peak currents and not the best beam quality caused by large $Z/n \sim 1\text{-}4\ \Omega$
- **Trends**
  - use of 3rd generation storage rings (Elettra...) with high quality beams ($\varepsilon_x \sim$ nm·rad, $\hat{I}_p \gtrsim 250$ A*, $Z/n < 0.1\ \Omega$)
  - use of helical wigglers (UVSOR, Elettra, Duke....) providing for 4× gain and less mirror degradation
  - long straights and long FELs ($\gtrsim 20$ m)

→ **Gain > 100% in XUV**

1-100 W in 5-25 eV range

harmonics 15-250 eV range

5 exist, 1 in construction, 5 proposed

OK-4 UV FEL Performance

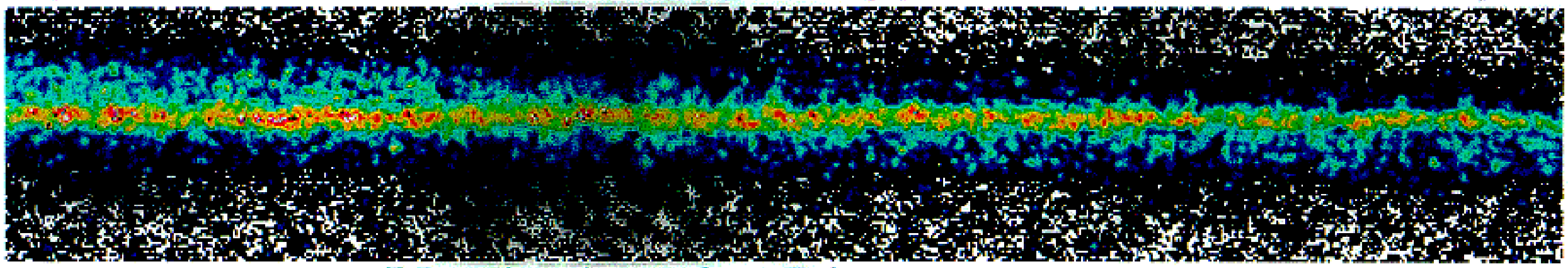
	Projected	Best demonstrated by March, 1999
Tuning range, [nm] fundamental:	50 - 800	217 - 730
Photon energies [eV]	1.5 - 25	1.7 - 5.7
Average laser power [W]	2-40 @ 100 mA	0.15 @ 16 mA *
Tuning range, [nm] harmonics:	4-100	
Giant Pulse rep-rate [Hz]	1-100	40
Power in Giant Pulse mode [MW]	100	0.1-0.3
Duration of macropulse [μsec]	30-100	100-200
Peak power in Giant Pulse [MW]	3-100	0.1-0.3
Peak power intracavity [GW]	1-10	0.1
Linewidth, [$\delta\lambda/\lambda$] natural	(1-3) 10^{-4}	10^{-4}
with linewidth narrowing	(5-30) 10^{-7}	3 10^{-6} (Novosibirsk)
Micropulse $\sigma\tau$ [psec] natural	3-30	2.5 - 60
Micropulse separation [nsec]	358.45- 5.60	358.45,5.60
Spatial distribution	TEMoo	TEMoo
Spectral Brightness [ph/sec/mm²/mrad²/10³·BW]		
Average	$5 \cdot 10^{24}$ (1 ppm BW)	(2-4)$\cdot$ 10^{20}
Peak (CW mode)	~10^{27}	$4 \cdot 10^{24}$
Peak (giant pulse mode)	~10^{30}	$3 \cdot 10^{26}$

***outcoupled, outcoupling efficiency (transparency/losses)<10%**

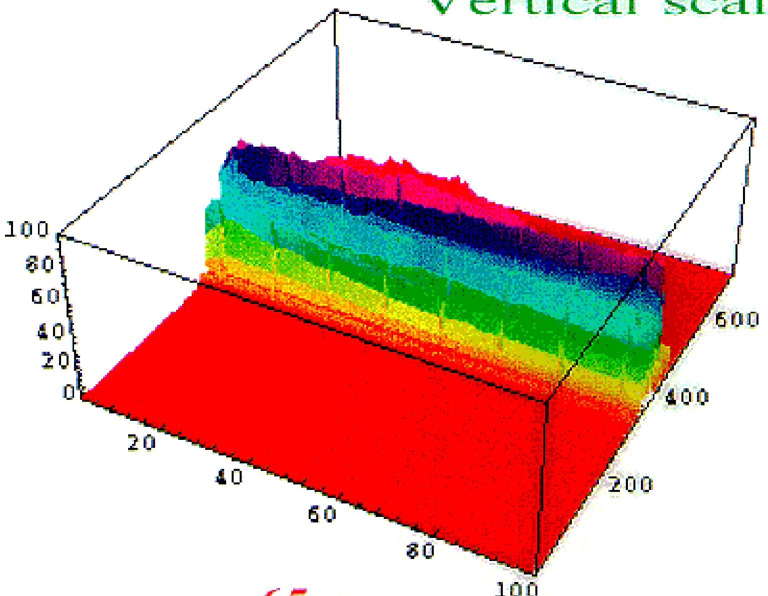
Fourier Limited FEL pulses -Super Modes

Predicted: G.Dattoli and A.Renieri, Nuovo Cimento B59 (1980) 1

<- 0.5 msec ->

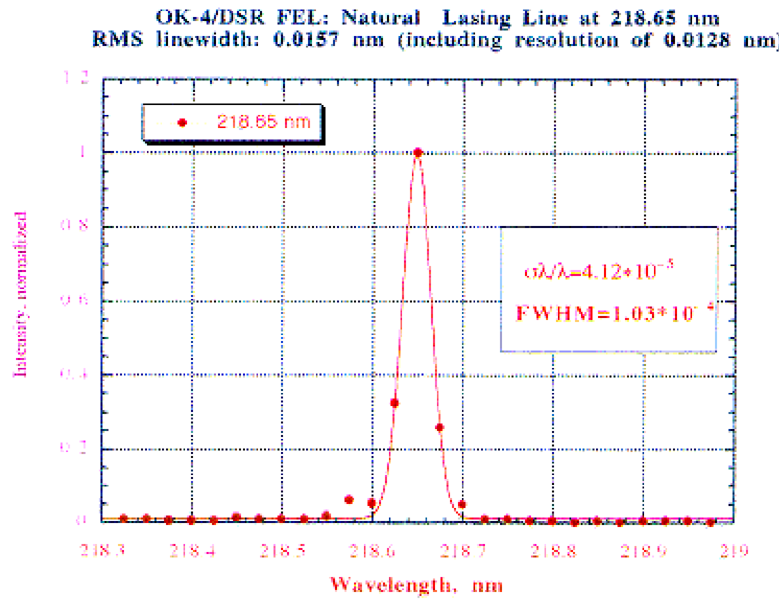


Vertical scale: 74 psec



$\sigma_{e\text{-beam}} = 65$ psec

$\sigma_{SM} \leq 2.4$ psec



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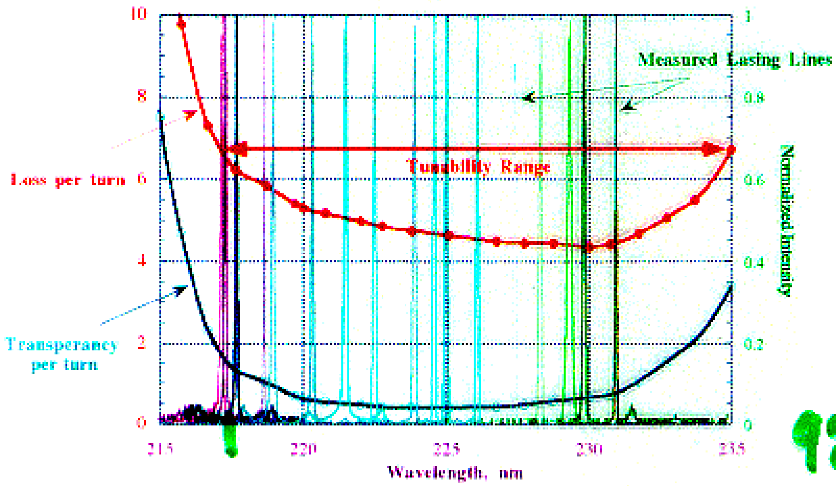
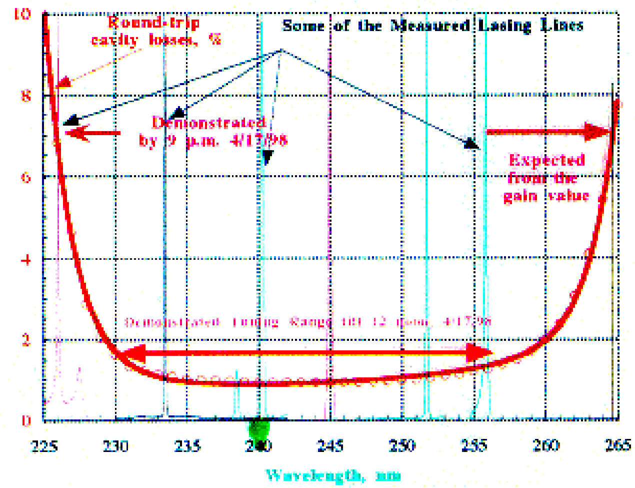
The OK-4/Duke SR FEL tunability

The OK-4/Duke SR FEL Loss curve, Lasing lines and Tunability around 225 nm



98

OK-4/Duke SR FEL Lasing around 245 nm



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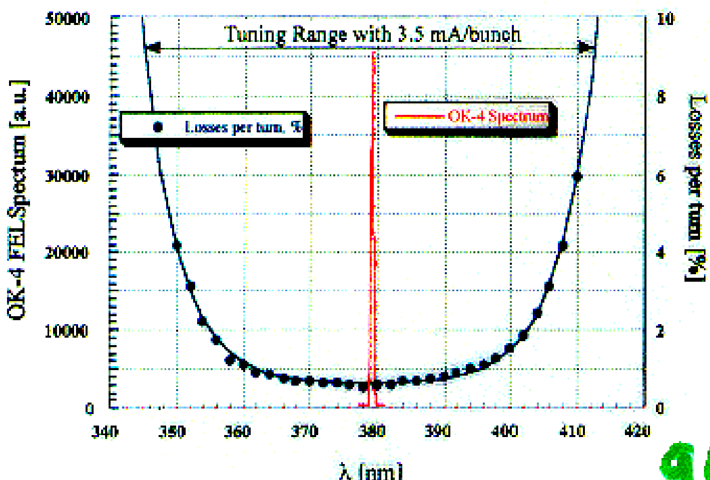
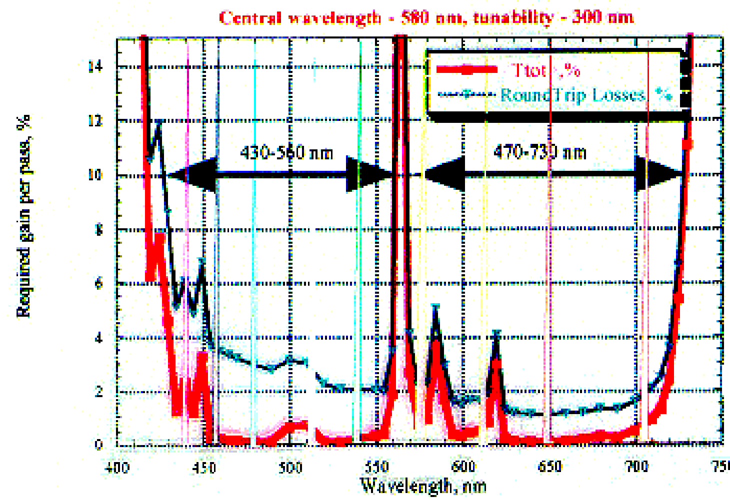


96

OK-4/Duke storage ring FEL - operation in the visible with broad band mirrors



99

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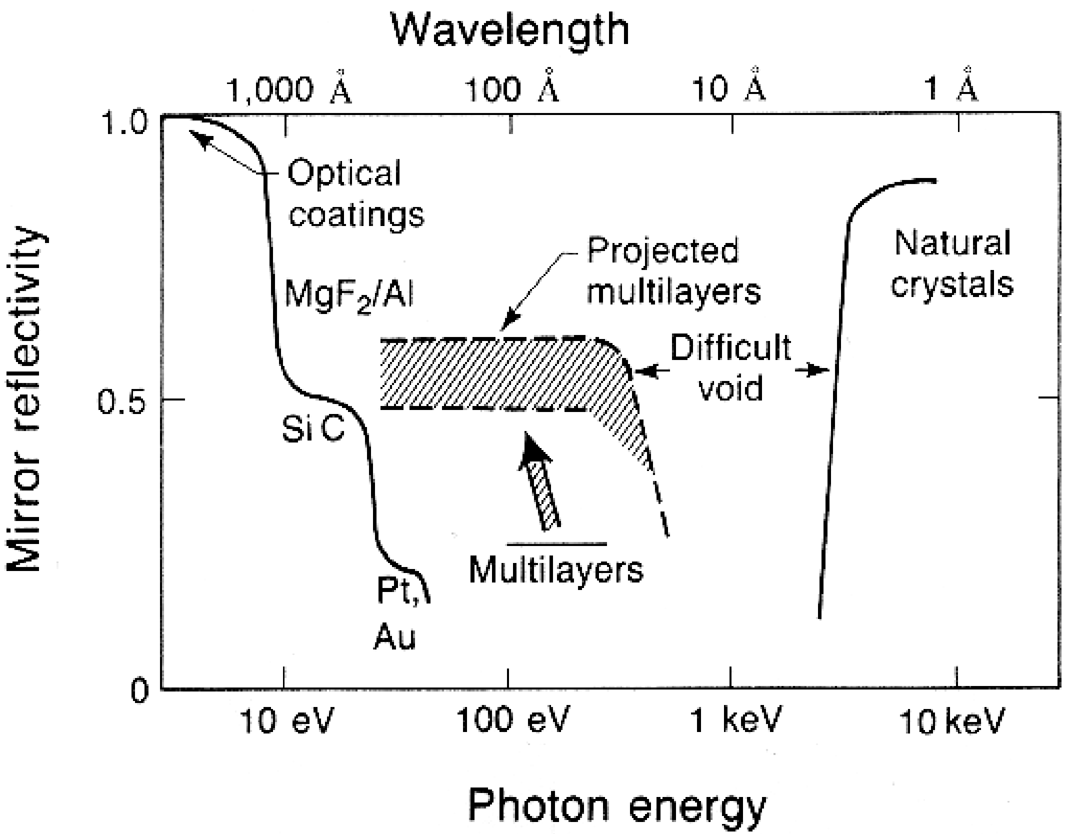
Cavity Mirrors Do Not Exist For Convential VUV or Soft X-Ray Free Electron Lasers:



Eph, eV	Gain req, %
10	~100%
100	~400%
3 keV	~100%

XBL 845-1715A

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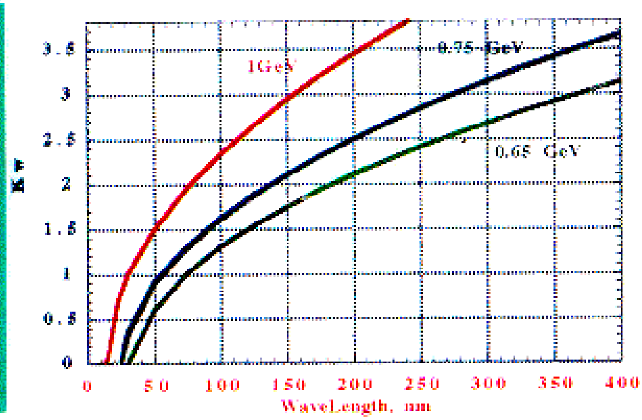
OK-5 UV-XUV FEL Performance

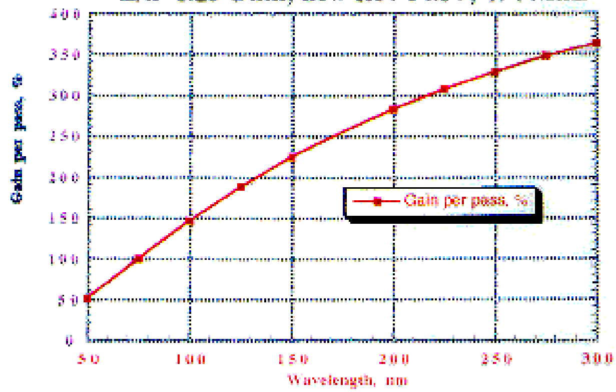
Polarization: *Circular & Elipctical (L/R), Linear(X,Y)*

Total length	[m]	20.5
Wigglers		*4*
Period	[m]	0.12
Length	[m]	4.04
Magnetic field	[kGs]	0-2.8
Kw		0 - 3.14
Tuning range	[$\lambda_{max}/\lambda_{min}$]	1 0.7
Bunchers		*3*

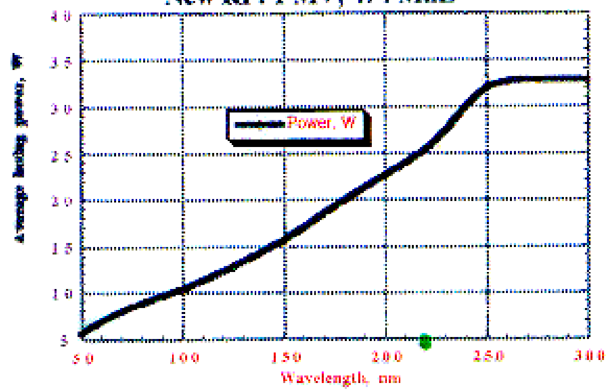
The OK-5 FEL Tuning Curves



The OK-5/DSR XUV FEL gain:
800 MeV; 20 mA/bunch;
Z/n=1.25 Ohm; new RF: 1 MV, 474 MhZ



The OK-5/DSR XUV FEL ~~gain~~:
800 MeV; 10 bunches; 20 mA/bunch;
New RF: 1 MV, 474 MhZ



Duke Storage Ring Group

Next Generation LS has one of those:

- higher average flux, brightness
- higher peak flux, brightness
- better transverse coherence (<u>TEM$_{00}$</u>)
- better longitudinal coherence (<u>FLB</u>)
- better time resolution (< ps)
- new photon energy range
- or combination of above

Opinions: 10th ICFA workshop on 4th GLS 1996

SR working groups

Reviews

M. Cornacchia
M.-E. Couprie
G. Decker
A. Jackson
J.-L. Laclare
M.-P. Level
L. Rivkin
A. Ropert
R.P. Walker
...

EPAC 1996
PAC 1997
APAC 1998
EPAC 1998
PAC 1999

- VUV (<1 keV) diffraction limited LS is feasible $\bar{B} \sim 6 \cdot 10^{22}$
- X-ray (10 keV) @ 7 GeV is ~50 times above diffraction limit
- Lattice (DBA, TBA, MBA, TME, ...) – opinions devided
- Top-up is feasible, but...
- **Touschek Lifetime is The Problem**
- Dynamic aperture is a serious challange
- **Intra-beam Scattering is a main limiting factor for achieving very low emittances!**

$\varepsilon_x \longrightarrow$ min

Best demonstrated 1 Å·rad, ESRF, 1 GeV
VERY LOW CURRENT

"1992 design" in PEP tunnel (2.2 km)

$\varepsilon_x = 0.04$ nm @ 4 GeV

150 m long straights, 6 × 30 m wigglers

PAC 1999, A.F. Wrulich – Future Directions in Storage Ring Developments for Light Sources

2×APS
2×lattice
8 × (2 circ)
9.2 × 2T damp. wigglers
(L_w=208 m, λ_w=10 cm)

$\Rightarrow$ $\varepsilon_x = 0.054$ nm @ 7 GeV

VSX (Y. Kamiya et. all) $\varepsilon_x = 0.715$ nm·rad @ 1 GeV

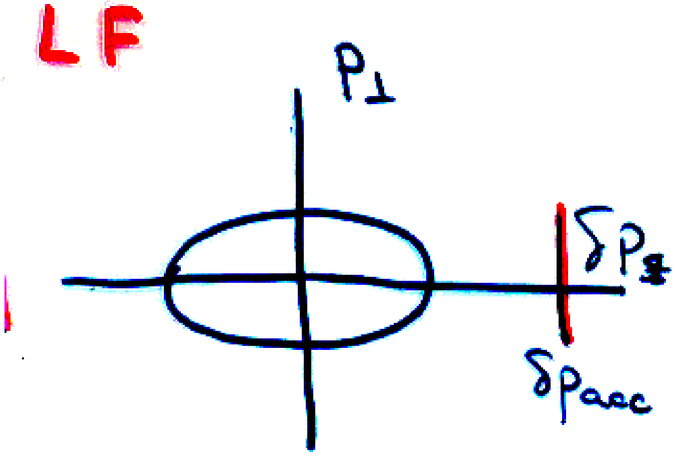
ATF (KEK) $\varepsilon_x = 1.6$ nm @ 1.3 GeV @ $\hat{I}_p = 150$ A – experiment

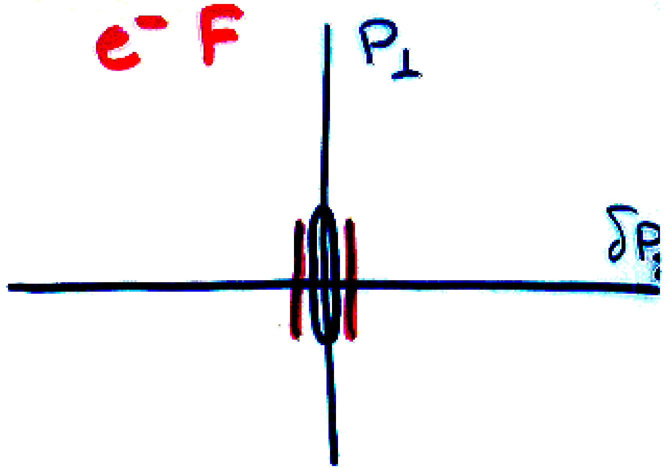
NLC DR (SLAC) $\varepsilon_x = 0.75$ nm @ 2 GeV @ $\hat{I}_p = 610$ A – simulations
(τ_L = 1 min)

($Q = 3$ nC, $\varepsilon_\gamma = \gamma\varepsilon_x = 3$ mm·rad)

Short List

- Touscheck Life Time → Low Energies !
- Damping @ low Energies
- Hard X-rays @ Low Energies
- fs - e-bunches





Touschek lifetime: J. Le Duff, CAS 1993 (1995) p. 573

$$\frac{1}{\tau_T} = \frac{N_e r_e^2 \cdot c}{8\pi \gamma^2 C} \cdot \int_0^C \frac{ds}{\sigma_x \sigma_y \sigma_s} \left(\frac{\Delta p}{p_0}\right)^3_{acc} \cdot D(\xi) \rightarrow g(s)$$

$\rightarrow f(s)$

$$\xi = \left(\frac{\Delta p}{p}\right)^2_{acc} \cdot \frac{\beta_x(s)}{\gamma^2 \varepsilon_x}$$

$$D(\xi) = \sqrt{\xi} \left\{ -\frac{3}{2} e^{-\xi} + \frac{\xi}{2} \int_\xi^\infty \frac{\ln u \, e^{-u}}{u} du + \frac{1}{2}(3\xi - \xi \ln \xi + 2) \int_\xi^\infty \frac{e^{-u}}{u} du \right\}$$

Ways to improve lifetime

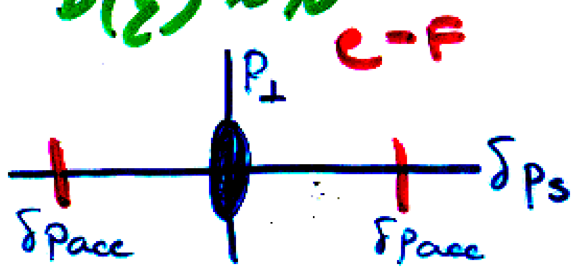
Conservative : $\tau_T \sim \gamma^2 \rightarrow$ increase $\gamma = E_e/mc^2$

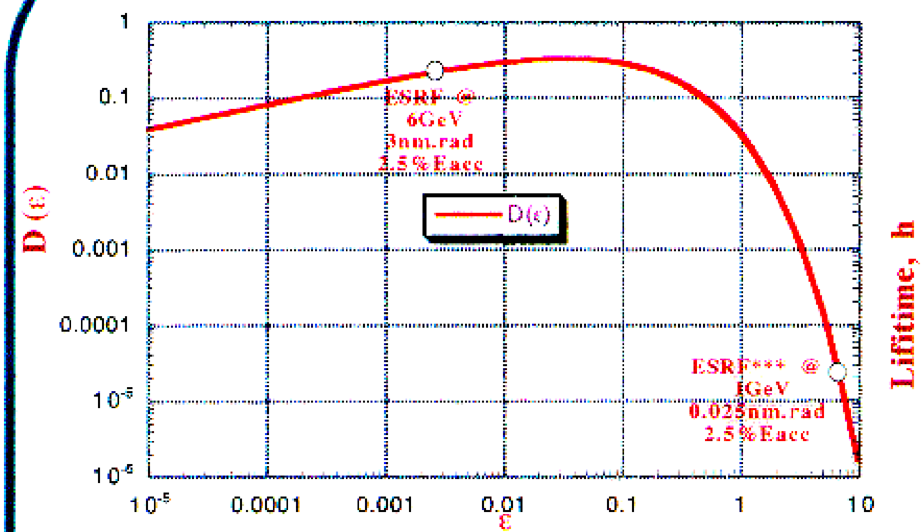
$\tau_T \sim \left(\frac{\Delta p}{p}\right)^{2\div 3}_{acc} \rightarrow$ increase $\left(\frac{\Delta p}{p}\right)_{acc}$

*** Expensive & limited to 2–10 fold increase

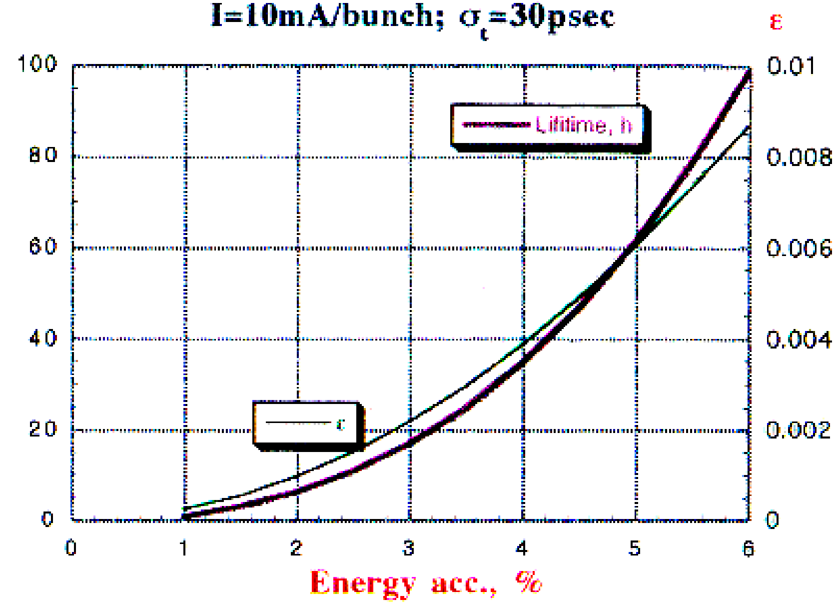
Radical : $\xi \gg 1 \Rightarrow D(\xi) \sim 10^{-4}$

$\Rightarrow$ Lower $\gamma^2 \cdot \varepsilon_x$

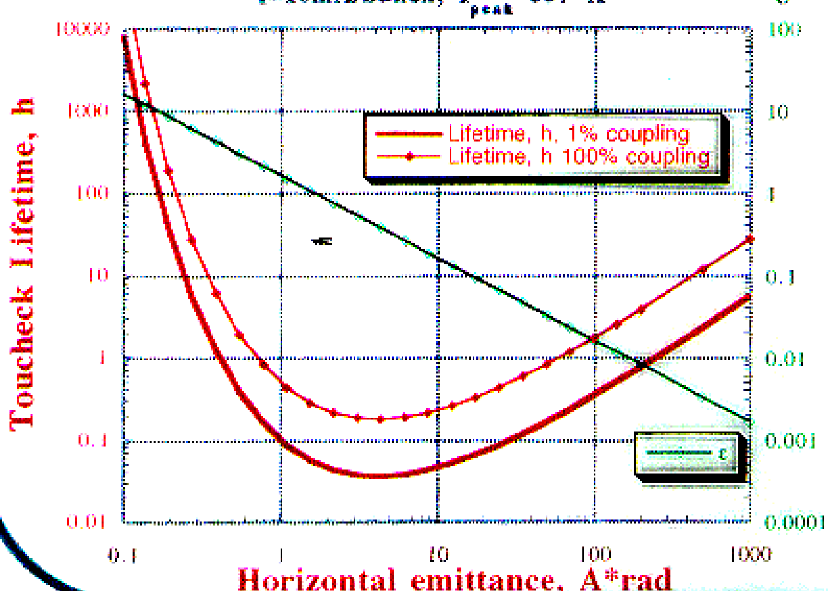




ESRF @ 6 GeV, ε_x=3 nm.rad,
I=10mA/bunch; σ_t=30psec



ESRF *** @ 1GeV, 2.5% energy acceptance;
I=10mA/bunch; I_{peak}=337 A



Lifetime would not be a problem for low energy machine with sub-Å emittances. It is the big question how to get there and how to preserve this emittance?

$$\gamma \leq \sqrt{\frac{10\beta_x}{\mathcal{E}_x}} \Big/ \left(\frac{\Delta p}{p}\right)_{acc}$$

V. Litvinenko

Intra-beam scattering limited beams

$\sigma^2 = \dfrac{\text{Diffusion}}{\text{Damping}}$

$$\varepsilon_x = \frac{D_{SR} + D_{IBS} + D_{ID} + D_{W} + \dots}{\gamma_{SR} + \xi_{ID} + \xi_{W} + \dots} \rightarrow \approx \frac{D_{IBS}}{\xi_{tot}}$$

ε_x : 100

$\underline{D_{IBS} \times 1000}$ $\rightarrow$ $\xi_{tot} = \dfrac{1}{\tau}$ $\underline{\times 100000}$

$$D_{IBS} = \int \frac{N_e r_e^2 m^2 c^5 \beta_x}{2^5 \pi \gamma \sigma_x^2 \sigma_y \sigma_s} \cdot H \cdot \frac{ds}{C} \cdot f(\chi_m)$$

$$H = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2$$

$$f(\chi_m) = \int_{\chi_m}^{\infty} \frac{1}{\chi} \ln(\chi/\chi_m) e^{-\chi} d\chi$$

$$\chi_m = \frac{r_e m c^2}{b_{max} \sigma_p^2}$$

$$D_{IBS} \sim \frac{\hat{I}_p}{\gamma \cdot \varepsilon_x \sqrt{\mathcal{X}\varepsilon_x}} \frac{\int H ds}{C}$$

$$\xi_{tot} \sim \gamma B_w^2 L_w$$

$\varepsilon_y = \text{const}$

$$\boxed{\xi_{tot} \sim 1/\varepsilon_x^2}$$

→ H=0 everywhere possible

→ long disp-free straight sections

→ filled with high field wigglers or CSS

V. Litvinenko

Review on Laser Cooling in the Storage Ring

Presented at FEL'98, Y. Wu and V. Litvinenko, Williamsburg, VA

Regular SR + one laser cooling section

$$\epsilon_x = \epsilon_{x0}\frac{1+f\alpha_{Qx}}{1+f}, \qquad \left(\frac{\sigma_E}{E_0}\right)^2 = \left(\frac{\sigma_E}{E_0}\right)_0^2 \frac{1+f\alpha_{QE}}{1+f}$$

where,

$$f = 8\frac{\rho r_e}{Z_R\lambda_L}\frac{E_L}{\gamma_0 E_0}, \qquad \alpha_{QE} = \frac{448\pi\sqrt{3}}{275}\frac{\rho}{\gamma_0\lambda_L} \qquad \alpha_{Qx} = \frac{96\pi\sqrt{3}}{275}\frac{\rho}{\gamma_0^3\lambda_L}\frac{\beta_x^*}{\overline{H}}$$

Reference: *Laser cooling in SR*, Zhirong Huang, Ronald D. Ruth, PRL, v.80, n.5, 1998;

Advantages for using FEL as an instrument for laser cooling:

- high intracavity power, natural alignment and synchronization;
- flexibility in laser wavelength selection;

Example: e-beam cooling using mm-wave FEL

- $\gamma_0 = 1000$, $\rho = 1$ m;
- $\lambda_L = 0.1$ mm, $B_L = 1000$ kG ($K_L = 1$), $Z_R = 0.2$ mm;
- $P_{IntraCavity} = 12$ GW, $\sqrt{2\pi}\sigma_l = 300$ ps, $E_L = 3.6$ J;

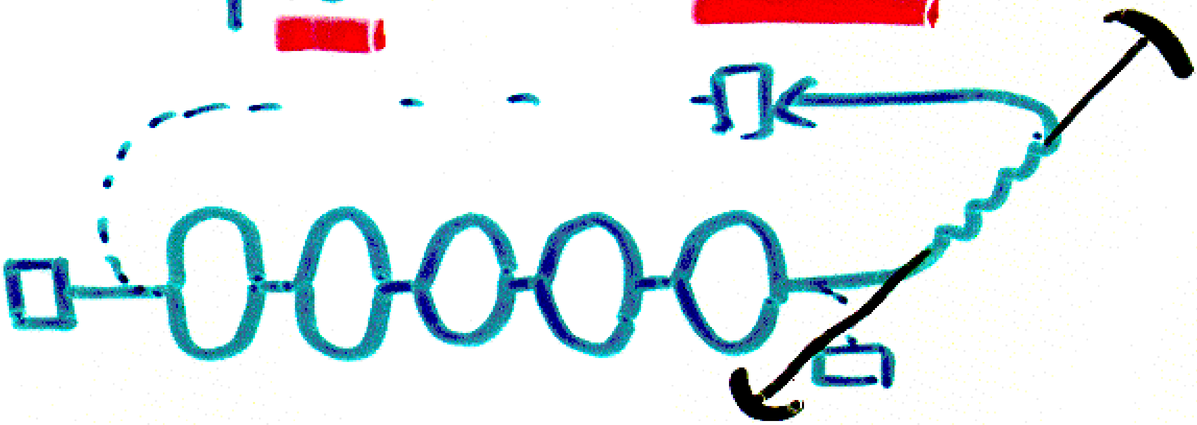
The beam sizes:
$\epsilon_x/\epsilon_{x0} = 0.018$, $\sigma_E/\sigma_{E0} = 9.5$.

$$\epsilon_x\text{: } 2 \text{ nm} \rightarrow 0.04 \text{ nm}, \ \sigma_E\text{: } 2\times10^{-4} \rightarrow 2\times10^{-3}.$$

New sources – sub-mm FELs

$\overline{P} > 1\,kW$ up to $1\,MW$

DC, RF or SCRF



- use intracavity power
  $\times\ Q = 10^3 - 10^4 \rightarrow$ (MW – GW)
- duty factor $\times\ 10^2 - 10^3 \rightarrow$ (GW – TW)

$\Rightarrow$ peak power ~ 1 GW – 1 TW

λ – tunable 0.1 mm – 10 mm

Polarization – selectable

IDEAL TEM-wave in vacuum

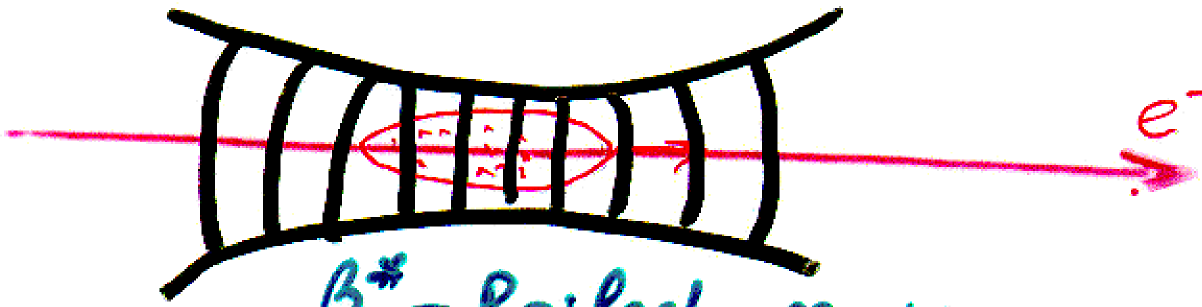
WIGGLER!

Sub-mm FEL Power

USEFUL for: damping

TEM-wiggler: X-ray production

IFEL : strong longitudinal focusing



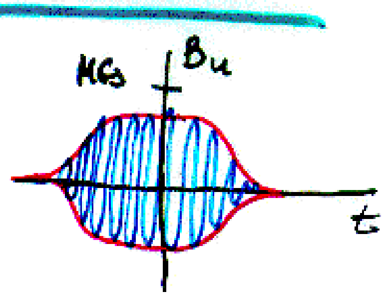
β^* – Rayleigh range

1. Field is plane ⇒ no non-linear tune shifts!

$$\Delta \vec{A} = 0 \quad \Longrightarrow \quad \Delta \vec{A} = \frac{1}{c^2}\frac{\partial^2 \vec{A}}{\partial t^2}$$

---

2. $\hat{P} = 13.7\,\mathrm{GW} \cdot K_u^2 \cdot \beta^*/\lambda$



$\beta^* \sim \sigma_s \sim 1_{cm}$ $\quad \lambda = 1\,\mathrm{mm}$

$B_u \approx 100\,\mathrm{kGs}$ @ $\hat{P} = 157\,\mathrm{GW}$

$\hat{P} = 1\,\mathrm{TW} \rightarrow B_u = 0.25\,\mathrm{MGs}$

EPAC '96
L. Rivkin

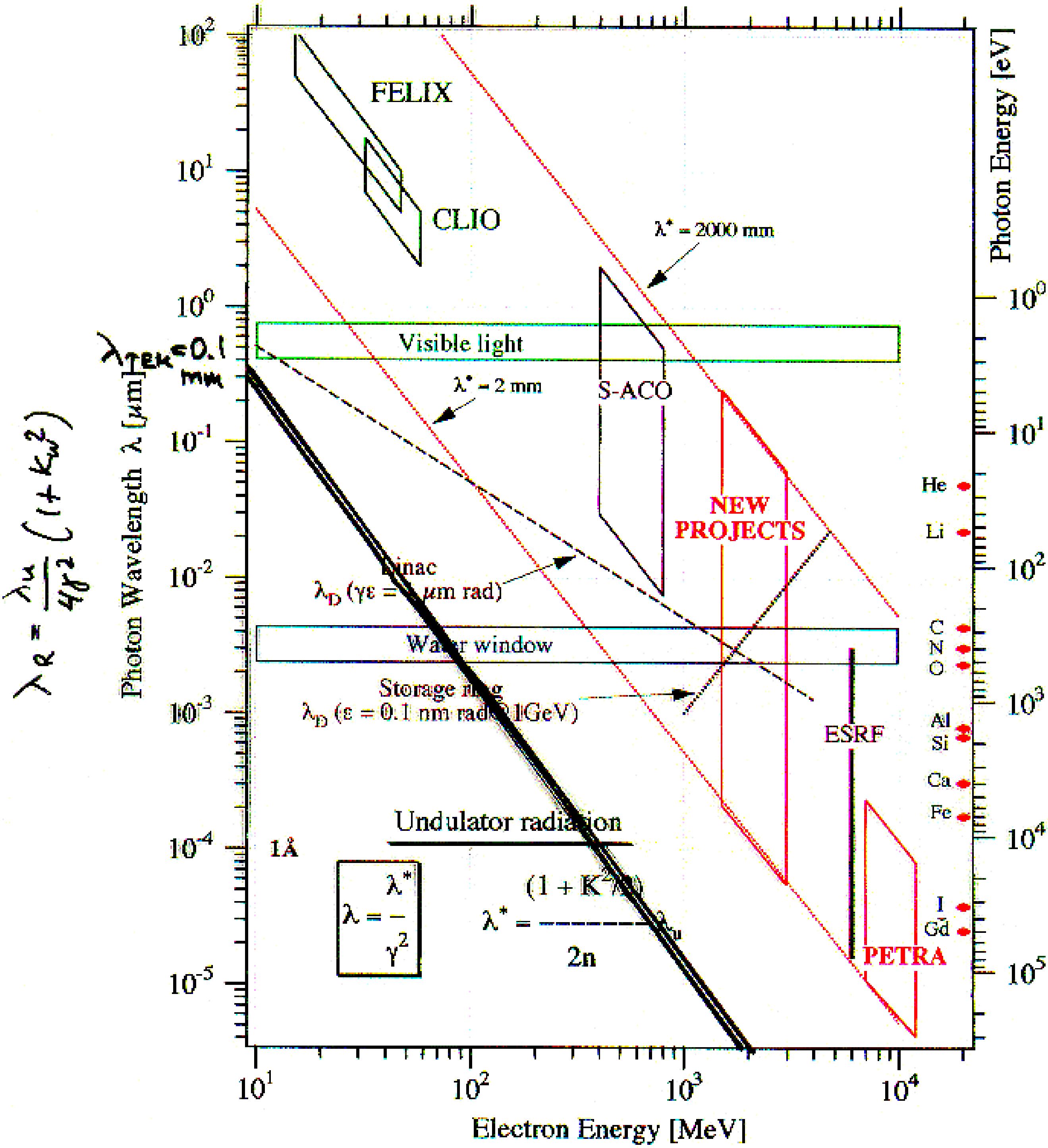
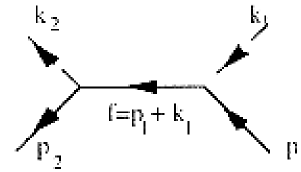


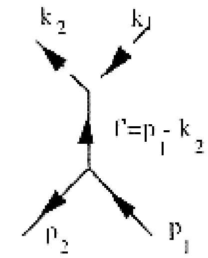
Figure 1: Universal undulator radiation diagram. The wavelength ranges of undulator radiation attainable at the European synchrotron radiation sources (including the future projects). Radiation wavelength is plotted against the electron energy on a log log scale. The two dotted parallel lines represent the range accessible at a given energy. As a lower limit, an undulator with effective period of 2 mm is chosen (e.g. period of 18 mm, ninth harmonic and K = 1.4). The upper limit is represented by an effective period of 2000 mm (e.g. period of 200 mm, first harmonic and K = 6). Diffraction limits for the linacs (normalised emittance of 10^{-6} m·rad) and for storage rings (0.1 nm·rad @ 1 GeV) are indicated in the plot. The K-absorption edges of some elements are shown as well.

W. Joho

Compton Back-Scattering



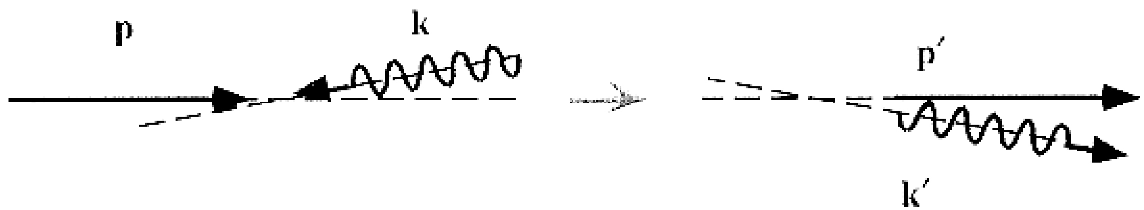
Before



After

$$\overline{\sigma}_{tot} = \frac{2\pi r_e^2}{x}\left\{\left(1-\frac{4}{x}-\frac{8}{x^2}\right)\ln(1+x)+\frac{1}{2}+\frac{8}{x}-\frac{1}{2(1+x)^2}\right\}, \quad \text{where } x=\frac{2\gamma\hbar\omega(1-\beta\cos\theta_i)}{mc^2}$$

γ-ray Energy



Scattered Photon Energy

$$\hbar\omega' = \hbar\omega\frac{1-\beta\cos\theta_i}{1-\beta\cos\theta_f+\left(\hbar\omega\Big/\gamma mc^2\right)\left(1-\cos\theta_{ph}\right)}$$

$$\theta_i = \cos^{-1}\left(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}}\right) \qquad \theta_f = \cos^{-1}\left(\hat{\mathbf{p}}\cdot\hat{\mathbf{k}}'\right) \qquad \theta_{ph} = \cos^{-1}\left(\hat{\mathbf{k}}\cdot\hat{\mathbf{k}}'\right)=\theta_i-\theta_f$$

Advantages of TEM waves-undulators

- **Hard X-rays can be generated at low e-beam energies <1GeV**
- **Sub-nm emittances at low energies ~~do~~ not reduce lifetime**
- **Use if intra-cavity power to enhance the flux**
- **Tunability of wavelength gives tunability of X-ray energy**
- **K~1 at wavelength of 0.1 mm and tunable polarization**

V. Litvinenko

Conclussions: of 4th GLS, A^{E}PAEs $\frac{1996}{1999}$

- Low or negative α_c does not provide for intense sup-ps e-bunches in storage rings
- Coherent synchrotron radiation is the main limiting factor for bunch-shortening (in addition to more traditional wakefields & α_2)

Strong Longitudinal Focusing

Presented at PAC'97, Y. Wu and V. Litvinenko

Condition for strong longitudinal focusing:

$$\nu_s = \frac{\mu_s}{2\pi} \sim 1, \quad \text{OR,} \quad \frac{|eV_{RF}|}{E_0} k_{RF} C \alpha_c \sim 0.1 - 1$$

The effective way to increase the longitudinal focusing is by

- decrease λ_{RF}: very promising with mm-wave (e.g. IFEL)

Two types of cavities:

- Active primary cavities to compensate energy loss ($\lambda_{RF} \sim 1$ m)
- Reactive strong focusing cavities to provide beam focusing ($\lambda_{RF} \sim$ 1 mm)

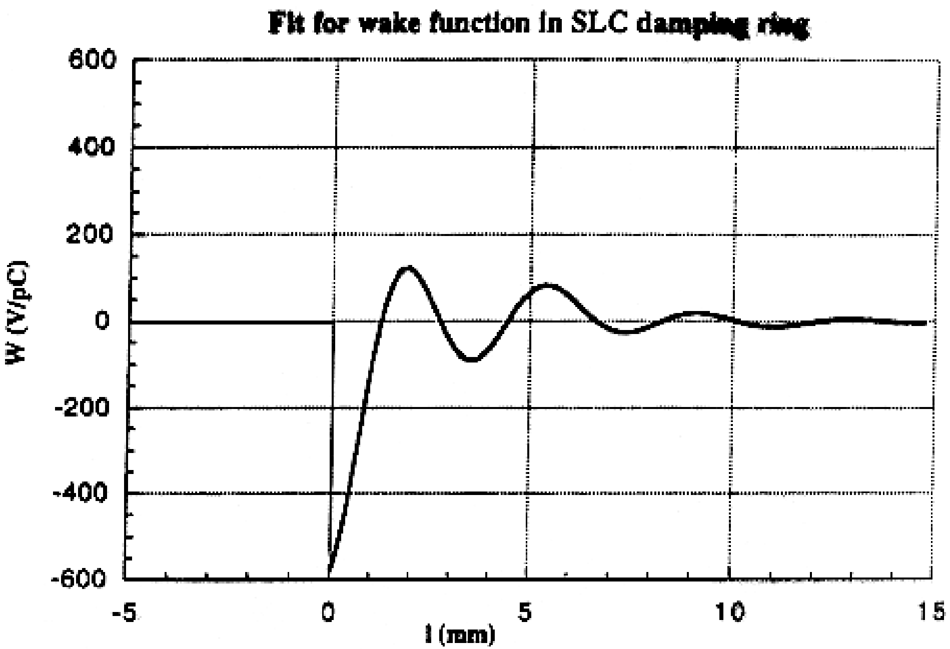
Inverse FEL as Strong Focusing RF

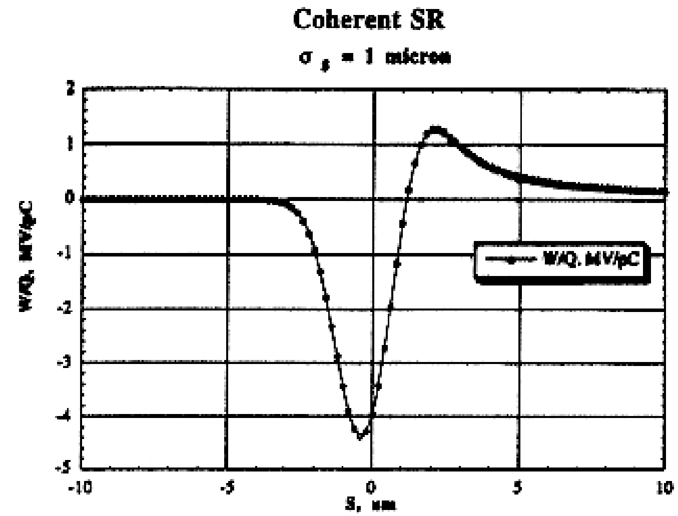
Example: at $E_0 = 1$ GeV, 0.1 mm FEL generated by a 4 period helical wiggler with $\lambda = 40$ cm and $B_0 = 11$ kG.

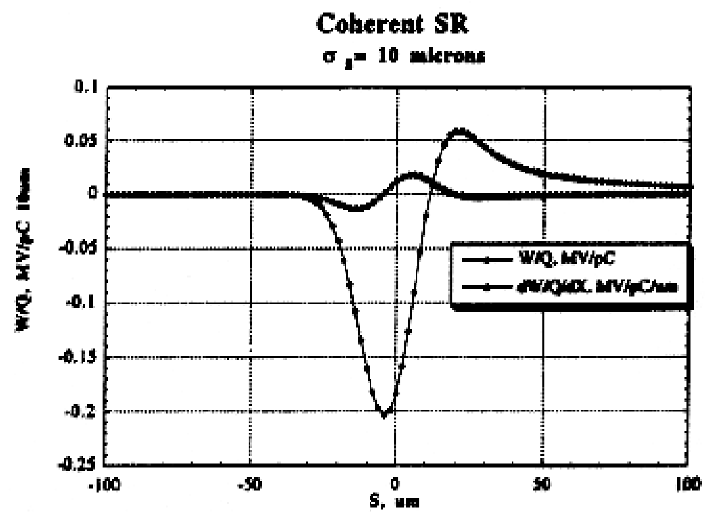
To generate $V_{RF} = 10$ MV, it requires

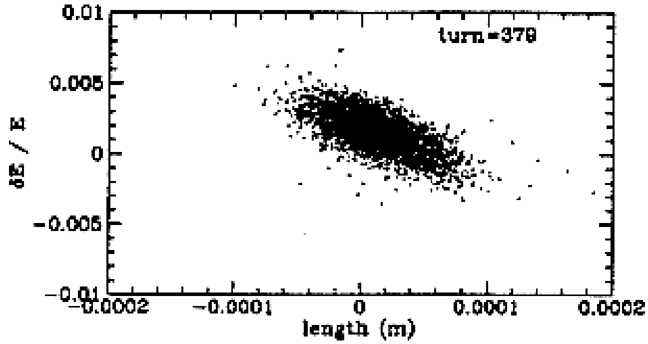
- a peak FEL power: 1 GW;
- an average FEL power: 1 kW (for a cavity with $Q \sim 1000$, duty factor 1000).

Coherent Synchrotron Radiation

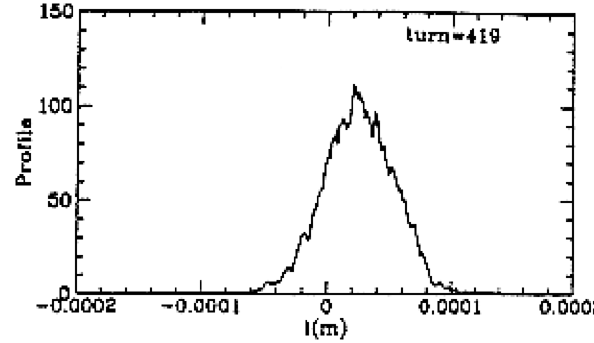




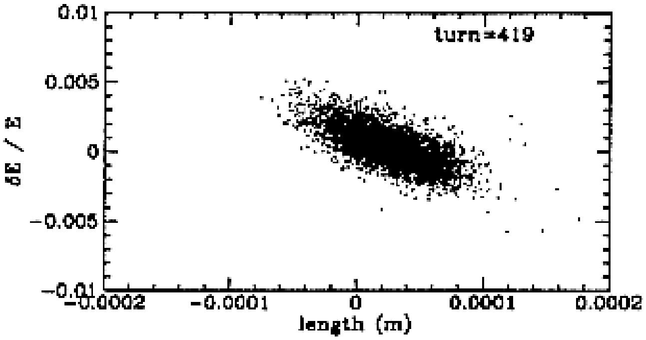




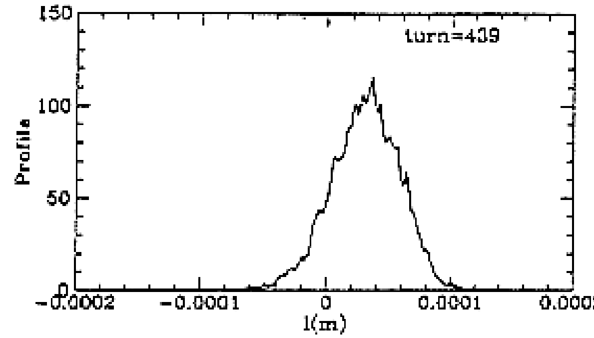
$\epsilon(\mu m) = 0.0766026$ $\alpha = 0.370592$
$\sigma_E = 0.00129239$ $\sigma_l\ (mm) = 0.0632112$



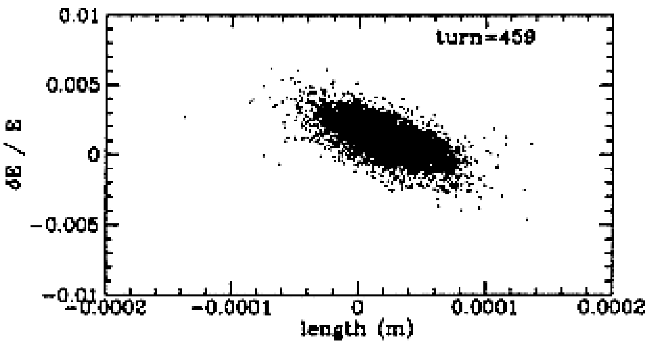
$\epsilon(\mu m) = 0.077314$ $\alpha = 0.36834$
$\sigma_E = 0.001314$ $\sigma_l\ (mm) = 0.062705$



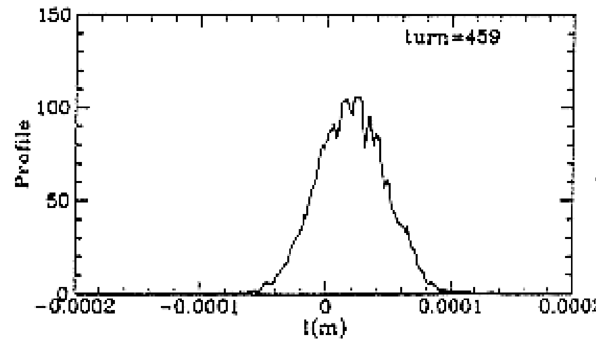
$\epsilon(\mu m) = 0.0773137$ $\alpha = 0.368341$
$\sigma_E = 0.00131397$ $\sigma_l\ (mm) = 0.0627046$



$\epsilon(\mu m) = 0.078901$ $\alpha = 0.25638$
$\sigma_E = 0.001316$ $\sigma_l\ (mm) = 0.061892$



$\epsilon(\mu m) = 0.078272$ $\alpha = 0.330815$
$\sigma_E = 0.00129099$ $\sigma_l\ (mm) = 0.0622292$



~200fs

$\epsilon(\mu m) = 0.078272$ $\alpha = 0.33082$
$\sigma_E = 0.001291$ $\sigma_l\ (mm) = 0.062229$

$E = 1\ GeV$ $I_{p(ini)} = 100A$

$f_0 = 1.5\ MHz$

$\alpha_c = 10^{-3}$

stable beam: $\sigma_\tau = 207 fs$

$\sigma_E/E = 1.3 \cdot 10^{-3}$

8 Strong focusing Cavities

$V_{RF} = 8 MV$

$f_{RF} = 300 GHz$ (1 mm)

$\nu_s = 1.52$

Conclussions:

- 3rd & 2nd GLS are the success of ring-based technology
- Diffraction limited ring-based light source for $\varepsilon_{ph} > 1$ keV ($\varepsilon_{x,y} <$ 1Å·rad) with $\bar{B}_s \sim 10^{22}-10^{24}$ is too attractive to avoid trying!
- Storage ring FELs (working on fundamental & harmonics) with 1-100W of average power would be excellent choice for fully coherent (both transverse & longitudinal) light source < 1 keV with $\bar{B}_s \sim 10^{21}-10^{25}$ & peak $B_s \sim 10^{30}$.
- Top-up can solve life-time problems for low-emittance, high peak current rings
- "Flat-RF" bunch-lengthening is usefull for high average brightness LS with low peak brightness - it can improve life time x100
- low energy rings with sub-Å emittances (if possible!) will escape from Touschek life-time problem. Use of sub-mm TEM waves as ID will make them contender for hard-x-ray users.
- VERY strong damping is required to reach sub-Å emittances - novel ideas wellcome!
- fs pulses could be generated in the rings via mm-wave (FEL RF

V. Litvinenko

There is the light ahead of us...